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Towards Greener Riprap: Environmental Considerations from Microscale to Macroscale

F. DOUGLAS SHIELDS, Jr, C. M. COOPER and SAMUEL TESTA, III

US Department of Agriculture,
National Sedimentation Laboratory,
Oxford, MS, USA

ABSTRACT

Effects of riprap on riverine fish and macroinvertebrate habitats are strongly related to spatial scale. Three scales are recognized: areas approximately equivalent to the median stone diameter squared (microscale), areas on the order of the square of the channel width (mesoscale), and channel reaches at least ten or more channel widths long (macroscale). At the microscale, riprap typically supports dense, diverse populations of macroinvertebrates and compares favorably with natural bank sediments and woody debris as invertebrate substrate. Biological density and diversity appear to be positively correlated with the range and maximum of riprap stone size. Available evidence from rivers in the United States indicates that mesoscale habitats provided by intermittent structures such as spur dikes are superior to those provided by continuous revetments. Macroscale effects of comprehensive planform stabilization of large rivers on bed material size and cross-section shape (and thus frequency distributions of depth and velocity) have not been clearly established for all stabilized river systems, but drastic reductions in riverine wetlands and backwaters have been widely observed.

1 INTRODUCTION

Riprap is a fundamental tool of mankind for development and control of rivers, streams, and canals. This paper describes effects of riprap on habitats of macroinvertebrates and fishes in riverine ecosystems. The nature of these effects is strongly related to spatial scale. Three scales are recognized: areas approximately equivalent to the median stone diameter squared (microscale), areas on the order of the square of the channel width (mesoscale), and channel reaches at least ten or more channel widths long (macroscale). Small-scale effects reflect modifications to local hydraulic conditions; as scale increases, impacts on geomorphological processes become important. Below we relate the reported biological effects of riprap to physical phenomena, at least by hypothesis.

The effects of replacing natural vegetation and bank soils in riparian zones with riprap are important at all scales and are manifest in aquatic as well as terrestrial communities. However, we have limited

River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone
Edited by C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynord and K. W. Pilarczyk.

the scope of our discussion primarily to aquatic habitats and species, and, therefore, little space is devoted to effects above the water's edge. Obviously, this is an artificial distinction. Natural bank and riprap structure habitats are compared herein; much of the value of natural banks is due to overhanging cover, root wads, woody debirs, and coarse particulate organic matter (leaves and twigs) provided by trees and shrubs.

2 MICROSCALE

Flow forces are stressful for many aquatic organisms (Statzner et al., 1988) and, consequently, organisms that lack very streamlined body morphology seek out zones of reduced shear stress and turbulence in order to conserve energy. Sheltered microhabitats adjacent to flow fields that transport food and waste products to and from organisms are valuable habitats (e.g., a boundary layer adjacent to or within the surface layers of a riprap revetment). Visual observations indicate that flow adjacent to and within riprap structures in rivers is highly nonuniform. Nonuniformity is important because biological diversity is often associated with physical heterogeneity (e.g., Bournaud and Cogerino, 1986).

Quantification of physical heterogeneity adjacent to riprap is difficult. Data describing velocity fields at riprap blanket surfaces and within voids are scarce due to the difficulties of measurement (a review of techniques for such measurements in gravel stream beds is given by Williams and Hynes, 1974). Several investigators (e.g., Abt et al., 1991; Jain et al., 1988) report results of flume experiments where interstitial velocities for porous dikes or for rockfills placed on impervious embankments are measured using tracers or computed from head loss. Interstitial velocities are dependent upon hydraulic gradient and stone gradation; empirical relations have been derived from flume data. However, these relations are difficult to apply to bank protection because prediction or estimation of the local hydraulic gradient is problematic. Nevertheless, flow through rockfill voids is highly heterogeneous with laminar, turbulent, and transition regimes present (Jain et al., 1988); and void velocities are much lower than the channel velocities above and adjacent to the revetment. For example, Abt et al. (1991) measured interstitial velocities in flows just submerging riprap on slopes ranging from 1 to 20%. Median stone sizes ranged from 2.6 to 13.0 cm, and riprap layers were 7.6 to 30.5 cm thick. Mean interstitial velocities were 3 to 44 cm s^{-1}, which were two to three times lower than computed velocities for wide, open channel flows at similar depths and slopes with Manning's $n=0.3$. Williams and Hynes (1974) measured current velocity in a stream of 36 cm s^{-1} but an interstitial velocity 10 cm below the bed surface of only 0.1 cm s^{-1}.

Benthic aquatic species include invertebrates that burrow into soft sediments (infauna) and those that attach themselves to rocky surfaces (epifauna). Some epifaunal species and smaller vertebrates (e.g., juvenile fishes), spend at least part of their life cycle in voids within matrices of noncohesive particles like a riprap structure (Williams, 1984; Hjort et al., 1984; Li et al., 1984). Some evidence suggests that macroinvertebrate populations within a riprap structure are more dense and diverse than those found on its outer surfaces (Mathis et al., 1982).

The number and type of epifaunal organisms on and in a natural sediment deposit in a stream reflects sediment particle size, size gradation, and particle stability (Minshall, 1984). If a riprap structure is stationary relative to natural movable beds, it follows that riprap gradation is the dominant microscale habitat factor for a given set of hydraulic conditions. Results of experiments using uniform artificial stones suggests that the population density and species richness of benthos respond to stone size in a complex fashion: both are higher for small rocks placed alone in the flow, but when aggregate deposits are considered, larger stones support higher densities (Figure 34.1). Minshall (1984) suggested that this phenomenon was due to the association of larger (and thus possibly more habitable) voids with larger particles. Others have pointed out that physical complexity generally increases with median particle size; physical heterogeneity implies more habitat niches are available, and thus a more diverse biological community may result.

Riprap revetments in sediment-laden streams often become locations for sediment deposition (Tockner, 1991; Fisher et al., 1991; Shields, 1991).

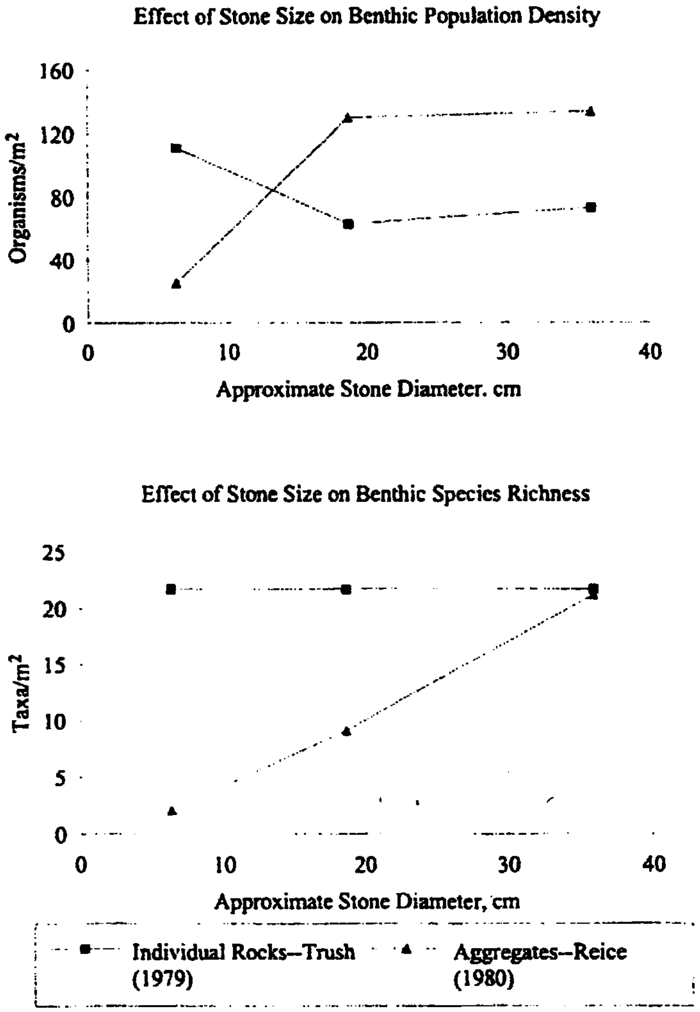

Figure 34.1 Effect of stone size on benthic diversity and density. The effect is different for individual stones and aggregates, suggesting that voids within the aggregate matrix become more habitable as stone (and thus void) size increases. After Minshall (1984)

Thin layers (~1 mm) of fine sediments and algal growth on riprap surfaces provide "secondary substrate" that is utilize by benthic invertebrates. In addition, sediments deposited in riprap interstices can enhance habitat and benthic species diversity (Burress et al., 1982; Mathis et al., 1982), but sand deposits that cover riprap reduce habitat quality (Sanders et al., 1986). When placed is sand-bed systems with little naturally occurring sediment larger than sand, riprap provides an otherwise unavailable or very scarce stable substrate for invertebrate production (Witten and Bulkley, 1975).

Copious literature attests to the ecological value of microscale riprap habitats to invertebrates, and a sample of findings for large US rivers is provided in Table 34.1a. Riprap substrates compare favorably with natural banks as benthic habitat. The cited authors described the sampled "natural bank" habitats as steep, eroding banks that are typical of the types of habitats replaced by revetment; samples from stable banks and sandbars were not included. Generally, they reported that organisms inhabiting natural bank sediments were sampled by collecting sediment samples using various types of sampling dredges and returning the sediments to the laboratory for separation and processing of biota. Riprap was sampled using metal baskets filled with riprap and implanted on the riprap structures for a fixed period of time (Sanders et al., 1985), or by collecting all stones enclosed by an rectangular frame placed

Table 34.1 Mean benthic invertebrate species richness (and density in numbers per square meter in parentheses) for natural banks and riprap structures. Species richness and density values are means for a given location and a given time. Mean species richness values in different rows are not directly comparable because different sampling methods were used

(a) Natural banks and riprap revetments

River	Natural banks	Riprap revetments	Riprap/natural bank %	Source
Arkansas	22 (1737)	38 (853)	172 (49)	Sanders et al. (1985)
Willamette	33 (2043)	48 (19 619)	130 (476)	Hjort et al. (1984)
Upper Missouri	4[a] (68)	6[a] (1570)	150 (2300)	Burress et al. (1982)

(b) Natural banks and riprap spur dikes

River	Natural banks	Riprap spur dikes	Riprap/natural bank (%)	Source
Arkansas	22 (1737)	22 (900)	100 (193)	Sanders et al. (1985)
Upper Missouri	4[a] (68)	8[a] (3037)	200 (4467)	Burress et al. (1982)
Lower Mississippi	17 (4903)	not given (849–23 462)	(17–479)	Baker et al. (1988a and 1991

[a] Taxa enumerated by order only.

on the structure at random (Burress et al., 1982; Atchison et al., 1986; Hjort et al., 1984), although less quantitative methods (such as collecting all organisms from a fixed number of riprap stones) have also been used (Sanders et al., 1986; Baker et al., 1988b).

Woody debris is an important invertebrate habitat, particularly in sand-bed rivers. Benke et al. (1985) found that woody debris supported 60% of the total invertebrate biomass, although it accounted for only 4% of the habitat area in a low-gradient sand-bed river in Georgia. Baker et al. (1988a) found an average benthic macroinvertebrate density of 3121 m^{-2} representing an average of 21 taxa on large woody debris adjacent to natural banks on the lower Mississippi River. In the streams listed in Table 34.1, woody debris is usually more common along steep, eroding, natural banks than riprap revetments. Comparisons of habitat values of natural and revetted banks should allow for different woody debris densities. In channelized or unstable sand-bed rivers, riprap structures may partially serve the function (stable substrate for macroinvertebrates) that large woody debris does in relatively undisturbed rivers.

Microscale phenomena may also affect utility of riprap as fish habitat. Riprap size heterogeneity rather than mean size has been shown to be an important determinant of benthic fish habitat at artificial reefs in marine environments (Helvey and Smith, 1985). Farabee (1986) found that fish biomass catch per unit effort at a Mississippi River revetment constructed with 0.6 m diameter riprap was more than twice as great as for a similar revetment constructed with riprap fitting a 0.3–0.6 m gradation. Michny and Deibel (1986) and Schaffter et al. (1983) reported 30–90% fewer juvenile salmon were found at Sacramento River revetted banks than natural banks, and suggested that the rougher riprap surfaces prevented formation of low-turbulence zones preferred by the juvenile salmon for feeding. However, riprap locations showed higher numbers of fish species that preyed upon and competed with the juvenile salmon (Michny and Hampton, 1984). In another region, placement of riprap revetments created additional spawning sites for lake sturgeon (Folz and Meyers, 1985). Thus by altering near-bank flow fields, riprap revetments can induce shifts in fish species composition and relative abundance.

3 MESOSCALE

3.1 Revetments

At the channel-width scale, hydraulic conditions created by riprap structures can be beneficial or detrimental to habitat quality. Some investigators have suggested that riprap revetment placed on the outside of a bend induces formation of a narrower, deeper baseflow channel; conflicting data from the Sacramento River have been presented by Harvey and Watson (1988) and Buer et al. (1989). The overall biological impact of revetment depends upon the magnitude of channel alteration and the quality of the habit replaced by the revetment. Knudsen and Dilley (1987) compared summer and fall anadromous fish populations in five western Washington stream reaches before and after construction of riprap revetments. Fishes in smaller streams (mean discharge 0.4–2.4 $m^3 s^{-1}$) were adversely impacted—biomass (in grams m^{-2}) was reduced 26% in the revetted reaches, but increased 54% in unaltered control reaches. Effects were different for larger streams (mean discharge 4.9–11.6 $m^3 s^{-1}$): revetted reach biomass levels increased 227%, while control reach biomass increased only 30%. Since this study was limited to a short period of time (months), it may simply indicate that large and small stream communities respond over different times scales.

Local effects of revetment construction have also been studied. For example, Li et al. (1984) sampled adult fishes adjacent to natural banks, and continuous riprap revetments along the Willamette River, Oregon, and found 20 species near natural banks but only 10 adjacent to revetments, possibly due to more diverse physical conditions at natural banks. Additional studies that include comparison of fishes at natural and revetted banks are listed in Table 34.2.

3.2 Spur dikes and other intermittent structures

Studies comparing macroinvertebrate (Table 34.1b) and fish (Table 34.2) assemblages adjacent to continuous and intermittent bank protection structures have been performed in a wide variety of stream

Table 34.2 Mean fish species (mean numerical catch per unit effort) for natural banks (usually steep, eroding banks) and riprap revetments. Species richness values are means for a given location and a given time. Mean values in different rows are not directly comparable because different sampling methods were used. However, column-to-column comparisons in the same row are valid. Fishes were sampled by electrofishing unless otherwise noted.

River	Natural banks	Riprap spur dikes	Riprap revetments	Spur dike/ revetment (%)	Source
Willamette	13 (89)	not sampled	11 (281)	—	Hjort et al. (1984)
Willamette	20	9	10	90	Li et al. (1984)[a]
Sacramento	8 (21)	not sampled	10 (26)	—	Michny (1988)
Sacramento	10 (488)	not sampled	12 (330)	—	Schaffter et al. (1983)
Upper Missouri	8	14	10	140	Burress et al. (1982)[b]
Middle Missouri	not sampled	11 (26)	15 (66)	73 (39)	Atchison et al. (1986)[c]
Upper Mississippi	33 (41)	not sampled	33 (87)[d]	—	Farabee (1986)
Arkansas	10 (98)	13 (225)	13 (110)	100 (205)	Sanders et al. (1985)[e]
Batupan Bogue, Mississippi	25 (360)	25 (410)	18 (196)[f]	139 (209)	Knight and Cooper (1991)
Lower Mississippi	60	68	not sampled[g]	—	Baker et al. (1991)[h]

[a] Cumulative total number of species captured, not mean per site per sampling date.

[b] Electrofishing, hoop netting, seining, gill netting.

[c] Electrofishing. Hoop net results were similar.

[d] Two revetments were sampled. One was constructed with 30–60-cm diameter riprap, the other with riprap "that averaged" >60 cm diameter. The larger riprap site had mean numerical and biomass catches per unit of effort that were 130% and 250%, respectively, of the same values for the smaller stone revetment.

[e] Electrofishing. Use of additional sampling gears in areas around spur dikes yielded 16 additional species there.

[f] Structures sampled for this study were longitudinal toe dikes (windrows of stone placed parallel to flow along bank toes), and provided habitat similar to riprap blanket revetment placed on a graded bank.

[g] Lower Mississippi River revetments are articulated concrete mattresses (ACM) with riprap and asphalt on upper banks. Species richness for natural banks and those covered with ACM are similar (Pennington et al., 1983).

[h] Numbers shown are total numbers of species reported in literature. Fifty-five species have been reported for articulated concrete mattress revetments.

habitats. Readers unfamiliar with limitations of technology for sampling fish in rivers should be aware that data in Table 34.2 may reflect differential sampling efficiencies along different bank types, cyclical or climatic effects, etc. Also, species richness and catch per unit effort do not tell the whole story. For example, although investigators studying the Sacramento River found more species along revetments than natural banks, juvenile salmon preferred natural banks in significantly greater numbers Schaffter et al., 1983; Michny, 1988; US Fish and Wildlife Service, 1992). Nevertheless, the values in Table 34.2 are all means of data generated by repetitive sampling in time and space and represent the best information available.

Results presented in Tables 34.1b and 34.2 indicate that intermittent structures like spur dikes or groins usually provide aquatic habitats superior to continuous revetment and sometimes surpassing natural banks. The superior performance of spur-type structures as fish habitat is related to creation of stable pools (scour holes) at riverward tips (Witten and Bulkley, 1975; Knight and Cooper, 1991; Shields et al., 1993), creation of lentic (still water) habitat connected with the main stream (Backiel and Penczak, 1989), provision of a complex of depth-velocity-bed type combinations not found adjacent to continuous riprap blanket (Li et al., 1984; Beckett et al., 1983; Baker et al., 1988b), and preservation of portions of the natural bankline and associated riparian vegetation and woody debris (Li et al., 1984). Woody debris is an important determinant of mesoscale habitat quality. Higher levels of physical heterogeneity are associated with higher woody debris densities (Shields and Smith, 1992), and fish populations respond negatively to debris removal or absence (Angermeier and Karr, 1984; Hortle and Lake, 1983).

Li et al. (1984) examined the use of natural banks, continuous riprap revetments, and spur dikes in the Willamette River, Oregon, by larval fishes. Continuous revetments were poor habitat for larval fishes relative to natural banks, while spur dikes were of intermediate quality due to the physical heterogeneity generated by the typically complex flow patterns around the spurs. Shallow zones above the gradually sloping bars adjacent to the spur dikes were particularly good habitat. Similar findings were reported by Schiemer and Spindler (1989) for the Danube in Austria. Geometrically complex banklines along the Danube River that included gravel banks and littoral bays supported higher densities and diversities of juvenile fish than adjacent riprap revetments. Twelve species were captured from gradually sloping gravel banks and twelve species were also found in small bays in the inshore zone, but riprapped banks produced only three species.

3.3 Restoration and innovation

Because of the mesoscale effects described above, riprap structures have been widely used to rehabilitate aquatic habitats in streams damaged by channelization and erosion (Swales, 1989; Wesche, 1985). For example, Shields et al. (in Press) described habitat restoration for an incised channel in northwest Mississippi. Previous channel stabilization work (construction of a grade control structure downstream and placement of about 40 riprap groins) had been ineffective in restoring habitat quality. By adding low extensions to every other groin and placing a riprap toe along the opposite bank, scour hole volumes and depths were increased dramatically (Figure 34.2). For the same water surface elevation, mean maximum depth of scour holes at all 40 groins increased from 40 to 70 cm after restoration, and mean depth increased from 24 to 40 cm. After restoration the mean length of fish, number of fish species, and biomass catch per unit effort of electrofishing increased 81, 60, and 1142%, respectively (Shields et al., 1993). Favorable results for habitat restoration projects in channelized streams that featured riprap spurs and weirs have also been reported by Swales (1982), Edwards et al. (1984), and Carline and Klosiewski (1985). Design criteria are provided by Wesche (1985).

Innovative concepts for riprap structures—both intermittent and continuous—have been proposed to address economic, environmental, and engineering weaknesses of more orthodox approaches (Table 34.3). In general, these concepts produce mesoscale habitats superior to those found at more orthodox structures. However, all of them should be

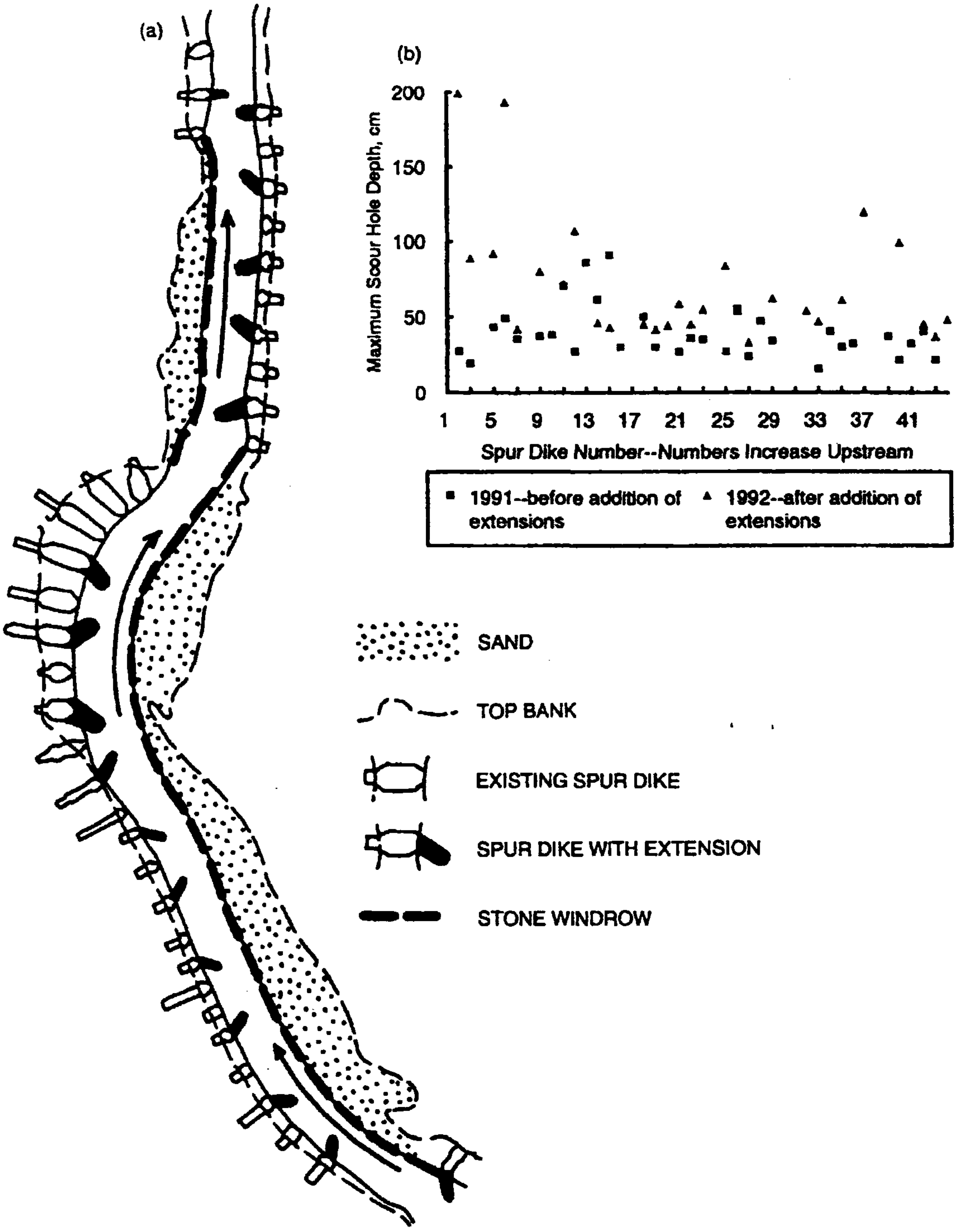

Figure 34.2 Modification of short riprap spur dikes at Hotophia Creek, Mississippi, to improve mesoscale habitats. (a) Stone added to modify habitat. Existing structures are unshaded, additions are shaded black. (b) Effect of spur dike extensions on availability of scour hole habitat. Maximum depth of scour holes at dike tips measured at nearly identical stages at midsummer before and after extension of every other dike

Table 34.3 Concepts for riprap structures with potential for providing mesoscale habitats superior to traditional designs

Concept[a]	Description	Objective	Benefits to habitat	Testing[b]	Remarks	Source
Bendway weirs	Submerged, level-crested spur dikes angled upstream	Develop and maintain navigation channel	Minimize disturbance of bank (shaping, clearing vegetation, etc.)	Model studies and prototype installation on middle Mississippi River, no biological studies	Developed expressly for a particular reach; applicability elsewhere may be questionable	Davinroy (1990)
Off bankline revetments	Windrows of riprap placed in shallow water a short distance from eroding with periodic gaps	Protect bank	Low-velocity habit created between structure and bank. Bank clearing eliminated. Gaps allow movement of organisms and recreational craft	Biological field studies on Middle Mississippi and Missouri Rivers	May be vulnerable to sedimentation. Stone requirements likely greater than for blank-type revetment	Niemi and Strauser (1991) Reynolds and Segelquist (undated) Kallemeyn and Novotny (1977)
Using larger stone gradation in traditional revetment	Upper end of gradation curve shifted to include a few large (–0.6 m) stones	Protect bank	Heterogeneity of voids increased. Large voids available for larger organisms.	Biological study at one field site	Potential adverse effects on revetment stability	Niemi and Strauser (1991) Farabee (1986) Kallemeyn and Novotny (1977)
Notched spur dikes	Gaps constructed or allowed to form in transverse training structures	Reduce sediment deposition in dike fields	Develop heterogeneous flow patterns and preserve low-velocity aquatic habitat contiguous with main channel	Several biological field studies that include limited physical data	Some locations are vulnerable to sedimentation or simply create additional high-velocity habitat	Shields (1984 and 1988)